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Soil Test Calibration for Predicting Corn Response to Phosphorus in the Northeast USA

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ABSTRACT

The consensus of soil fertility specialists working in the northeast USA was that soil testing and recommendation systems for P needed to be reexamined because of recent changes in soil testing methodology in the laboratory and corn (*Zea mays* L.) production technology in the field. Soil tests (M-COL, MM-COL, B-ICP, M1-ICP, and M3-ICP) were performed by either colorimetry or inductively coupled plasma (ICP) emission spectroscopy on samples from soil test calibration studies conducted during 1998 to 1999 at 51 experimental sites chosen to represent a range of soils, including Ultisols, Spodosols, and Alfisols, in northeastern states (Connecticut, Delaware, Massachusetts, Maryland, Maine, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia). The mean P measured by M-COL, MM-COL, B-ICP, M1-ICP, and M3-ICP was 8.3, 6.6, 148, 66, and 121 mg P kg^{-1}, respectively. Production practices followed local state extension recommendations at each site and included P fertilizer treatments: none, 15 kg P ha^{-1} banded, or 60 kg P ha^{-1} broadcast. Combined analysis of variance over sites showed that plant height at 35 d after planting, silk emergence, grain yield, and grain dry down were enhanced by the broadcast P treatment. There were yield increases ($P < 0.10$) to the band treatment at only four sites and to the broadcast treatment at nine sites. Cate-Nelson statistical analysis of relative yield in relation to soil test P failed to identify soil test P critical levels for any of the soil test methods. The percentage of experimental sites that had soil test P levels below the currently used critical levels in the region ranged from 14 to 65% of the sites. Results showed that 17 to 47% of those sites testing below the critical level exhibited a yield increase ($P < 0.10$) to broadcast P. Some of the yield responsive sites had soil test P above currently used critical levels. The calibration data obtained from the present study and the relationships examined between soil test P and relative yield do not necessarily validate the currently used soil test P critical levels nor does the data enable much refinement. This study shows that the current critical levels frequently permit both types of errors in soil test prediction; indicating a need for P fertilization when it may not be needed and not indicating a need for P fertilization when it may be needed. The second type of error is usually avoided by recommendations for crop removal rates of P.

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When soil testing programs began around the middle of the 20th century, collection of soil test field calibration data was a major research activity (Hanna and Flannery, 1960; Hanway, 1963). A considerable amount of data was collected and became the working and living knowledge of practicing agronomists of the era. Much of the data that was collected was kept in personal files and seldom published in peer reviewed journals. As a consequence, much of this body of soil test information was not effectively transferred to the next generation of agronomists.

Although it is widely recognized that soil test information and fertilizer recommendations require continual updating and reevaluation (Peck and Soltanpour, 1990), there has been little current national or regional emphasis on soil test calibration research with the possible exception of the presidedress soil nitrate test (PSNT) (Magdoff, 1991; Heckman, 2002). This may in part be because soil test calibration research is perceived academically as lacking originality and as low priority, and grant funds to carry it out are limited. Yet its importance to farmers and the environment cannot be denied (Sharpley et al., 1994).

Federal and state support for soil test calibration research has greatly diminished. A symposium held at the American Society of Agronomy meetings (Voss, 1996) concluded that "if resources became available, it is strongly suggested that the research be done regionally as opposed to each individual state and that current data management systems be used so that at any future date the data and analysis can be reviewed and that research data can be added to the data bank."

There are five extractants that are widely used by university and private soil test laboratories that operate within the northeast region of the USA, and the soil test P critical levels associated with the various extractants

Abbreviations: B-ICP, Bray-P1 with inductively coupled plasma emission spectroscopy determination of extracted P; M-COL, Morgan with colorimetric determination of extracted P; MM-COL, Modified Morgan with colorimetric determination of extracted P; M-ICP, Morgan with inductively coupled plasma emission spectroscopy determination of extracted P; MM-ICP, Modified Morgan with inductively coupled plasma emission spectroscopy determination of extracted P; M1-ICP, Mehlich-1 with inductively coupled plasma emission spectroscopy determination of extracted P; M3-ICP, Mehlich-3 with inductively coupled plasma emission spectroscopy determination of extracted P; PSNT, presidedress soil nitrate test.

vary among individual states (Table 1). Several university soil test laboratories within the region have recently adopted the Mehlich-3 soil test based on correlations with previous soil test methods and with very limited field calibration research conducted on local soils. Another recent development in soil testing is the analysis of the soil test extractions by ICP in place of colorimetric analysis (Mallarino, 2003). Thus, given the developments in crop production technology, increasing corn yield levels, and soil test laboratory methodology, it is imperative that soil test calibration for P be revisited.

Previous calibration research, all based on colorimetric analysis, is available from several states. In Pennsylvania (Beegle and Oravec, 1990) calibration research based on 67 experimental sites found critical levels of 19 and 20 mg P kg^{-1} for the Bray-Kurtz P1 and Mehlich-3 extractants, respectively. An Iowa study (Mallarino and Blackmer, 1992) with 25 experimental sites found critical concentrations of 13 mg kg^{-1} for Bray-P1 and 12 mg kg^{-1} for the Mehlich-3 extractants. Data from a combination of field and greenhouse work conducted in Vermont and New York in the past 20 yr (Jokela et al., 1998) support a critical value of 4 mg kg^{-1} with the modified Morgan (VT) or Morgan (NY) extraction for P.

In most states P fertilizer recommendations are based solely on a P soil test; but in Vermont, Modified Morgan-extractable Al is used to adjust P fertilizer recommendations (Magdoff et al., 1999). Modified Morgan-extractable Al ("Reactive" Al) was introduced into the Vermont soil testing system in the late 1970s based on research by Lee and Bartlett (1977). More recent work (Magdoff et al., 1999; Jokela et al., 1998) further supported the use of extractable Al as an indicator of the P fixing capacity of the soil. So, in the Vermont system, for a given soil test P below the critical level, the amount of P recommended increases as the amount of reactive Al increases (Jokela et al., 2004). Research in the province of Quebec (Khiari et al., 2000) examined use of extractable Al to improve P recommendations for potato (*Solanum tuberosum* L.). They found that the P/Al ratio extracted with Mehlich-3 extractant was a better indicator of both crop response and environmental risk than extractable P alone.

The objective of this northeast regional project was to evaluate corn responses to banded and broadcast P fertilizer using current crop production technology and soil test methods, and to determine how well the currently used soil test P critical levels are able to predict when corn responses to P fertilization should or should not be expected.

MATERIALS AND METHODS

Field experiments were conducted on P fertilization of corn grown at 64 experimental sites over a 12 state area (Connecticut, Delaware, Maine, Maryland, Massachusetts, New Hampshire, New Jersey, New York, Pennsylvania, Rhode Island, Vermont, and West Virginia) during 1998 and 1999. Of the 64 sites, 13 sites were deleted from the study for various reasons such as animal damage or weather-related crop failure. Most of the trials were in farmers' fields, but six were conducted on experiment station land. Table 2 lists experimental sites and soils. Crop management practices were those normally used by the farmer (except P fertilization), provided they were in agreement with local extension recommendations and nonlimiting rates of N and K fertilizers were applied. Fields with a recent (>5 yr) history of manure application were excluded from use in this study. Each experimental site included treatments of 0, 15 kg ha^{-1} P banded, and 60 kg ha^{-1} broadcast as triple superphosphate. The banded P was placed 5 cm beside and 5 cm below the seed. Plots consisted of four rows (row width was 76 cm) with a minimum length of 8 m. The treatments were replicated four times in a randomized complete block design. Corn was planted between 15 April and 6 June. Conventional tillage was used at all experimental sites. Fertilizers were broadcast and incorporated immediately before planting by disk or chisel plow. Soil samples were collected in the spring from the 0- to 15-cm depth by randomly collecting 15 cores (2.25-cm diam.) from each control plot. Soil samples were air-dried and crushed to pass a 2-mm sieve. The University of Delaware Soil Test Lab analyzed all samples for soil pH,

Table 1. Current soil test P critical levels used to guide P fertilization of corn in each of the 12 states. The number of experimental sites testing below the critical level and the number of sites with yield increases below the critical level.

Soil test	Current critical level		Maximum soil test P level for which broadcast P is recommended‡	Sites below critical level	Sites below critical level with yield increase ($P < 0.10$)	
	State	P				
		mg kg^{-1}	mg kg^{-1}	no.	no.	%
Morgan-Colormetric	NY	4.5	20	23	4	17
	RI	4.5	20	23	4	17
	MA	7	20	29	7	24
Modified Morgan-Colormetric	VT	4	7§	26	6	23
	ME	5	20	29	7	24
	CT	7	10	33	7	21
	RI	7	10	33	7	21
Bray-1–ICP	PA†	30	45	7	3	43
Mehlich-1–ICP	NJ	23	45	13	4	31
	MD	25	50	15	4	27
	WV	25	100	15	4	27
Mehlich-3–ICP	PA	30	50	9	3	33
	NJ	36	69	11	3	27
	DE	NA	50			
	NH	30	50	9	3	33
	MD	50	100	17	3	18

† Bray-1 critical level that was used in Pennsylvania before changing over to the Mehlich-3 soil test on 1 Aug. 1991.
‡ A starter fertilizer containing some P may be applied at higher than these soil test P levels.
§ A low rate of starter fertilizer P is recommended for soil test P up to 20 mg kg^{-1}, higher under adverse conditions.

Table 2. Soil classification, soil test P with each of five extractants, and Modified Morgan and Mehlich-3 extractable Al at 51 experimental sites in 1998 and 1999. Soil test extractable P and extractable Al were measured either colormetrically or with an inductively coupled plasma (ICP) instrument, as indicated. Data were organized by ranking Mehlich-3 soil test P values from lowest to highest. All data are from the 0- to 15-cm soil sampling depth.

						Soil test extractable P†					Soil test extractable Al		
Experimental site-state	Soil series and taxonomy	Organic C	pH	M-COL	MM-COL	M-ICP	MM-ICP	B-ICP	M1-ICP	M3-ICP	MM-ICP	M3-ICP	M3 P/Al
				mg kg^{-1}									%
27-VT	Vergennes; Glossaquic Hapludult; clay; very-fine, mixed, mesic	2.0	6.44	1.2	3.1	4.2	4.4	13	8	7	23	808	1
19-NJ	Freehold; Typic Hapludult; sandy loam; fine-loamy, mixed, mesic	1.2	5.36	0.8	1.2	2.4	2.2	20	9	16	48	712	2
48-VT	Vergennes; Glossaquic Hapludult; clay; very-fine, mixed, mesic	2.4	6.23	2.5	1.0	6.0	4.6	14	17	18	9	964	2
50-WV	Lindside; Fluvaquentic Eutrudept; silt loam; fine-silty, mixed, mesic	0.9	5.45	1.9	1.1	2.8	2.8	21	11	19	30	905	2
23-PA	Berks; Typic Dystrudept; shale silt loam; loamy-skeletal, mixed, mesic	1.6	6.30	2.2	2.4	5.1	3.8	24	14	21	22	681	3
51-WV	Monongahela; Typic Fragiudult; silt loam; fine-loamy, mixed, mesic	0.9	5.63	2.4	1.4	3.3	3.1	20	12	23	23	846	3
10-MD	Hagerstown; Typic Hapludalf; silt loam; fine, mixed, mesic	1.1	6.14	2.5	2.2	4.2	2.9	29	9	23	28	660	4
1-CT	Woodbridge; Aquic Dystrudept; sandy loam; coarse-loamy, mixed, mesic	2.2	5.56	1.4	3.2	5.6	5.0	78	32	28	234	1549	2
16-NH	Occum; Fluventic Dystrudept; coarse-loam, mixed, mesic	1.5	5.81	0.8	2.1	2.4	2.4	68	27	29	166	1331	2
29-CT	Paxton; Oxyaquic Dystrudept; sandy loam; coarse-loamy, mixed, mesic	2.1	5.80	1.1	0.9	3.5	3.2	42	20	34	161	1830	2
9-MD	Mattapex; Aquic Hapludult; silt loam; fine-silty, mixed, mesic	1.2	5.93	3.6	2.9	5.8	4.5	42	14	36	34	731	5
14-ME	Nicholville; Aquic Haplorthod; sandy loam; coarse-silty, isotic, frigid	1.8	6.00	1.8	2.8	4.1	3.4	75	32	38	116	1401	3
2-CT	Woodbridge; Aquic Dystrudept; sandy loam; coarse-loamy, mixed, mesic	2.6	5.92	1.5	3.2	4.8	4.1	99	36	43	170	1554	3
36-MD	Bertie; Aeric Endoaquult; silt loam; fine-loamy, mixed, mesic	1.0	6.20	3.1	1.7	4.9	3.7	34	17	44	37	856	5
3-DE	Evesboro; Typic Quartzipsamment; mesic; coated	1.0	6.03	2.7	1.8	4.3	2.9	47	12	45	34	639	7
22-PA	Allenwood; Typic Hapludult; silty clay loam; fine-loamy, mixed, mesic	1.2	6.82	5.7	4.5	7.9	5.1	53	27	46	13	681	7
20-NJ	Quakertown; Typic Hapludult; silt laom; fine-loamy, mixed, mesic	1.1	6.44	4.8	4.4	6.3	4.8	69	35	49	24	776	6
24-PA	Linden; Fluventic Dystrudept; sandy loam; coarse-loamy, mixed, mesic	1.5	6.14	6.0	5.0	8.1	5.6	67	27	51	17	673	8
13-ME	Nicholville; Aquic Haplorthod; sandy loam; coarse-silty, isotic, frigid	2.4	6.10	2.9	3.7	5.6	4.4	124	51	56	100	1418	4
15-NH	Occum; Fluventic Dystrudept; coarse-loam, mixed, mesic	1.8	5.49	2.3	2.5	5.9	4.5	72	25	58	142	1130	5
39-NH	Occum; Fluventic Dystrudept; coarse-loam, mixed, mesic	2.2	6.20	1.6	0.7	4.0	2.7	63	19	62	67	1542	4
32-DE	Rumford; Typic Hapludult; loam; coarse-loamy, siliceous, thermic	0.6	5.43	3.7	2.6	5.2	3.9	55	20	64	48	754	9
33-DE	Matapeake; Typic Hapludult; silt; fine-silty, mixed, mesic	1.0	5.48	3.9	2.4	6.0	4.4	56	70	65	40	1180	5
42-NJ	Quakertown; Typic Hapludult; silt loam; fine-loamy, mixed, mesic	1.5	6.38	4.7	2.6	7.1	4.7	72	30	69	31	1105	6
4-DE	Evesboro; Typic Quartzipsamment; mesic; coated	1.0	6.53	4.5	3.1	5.8	4.0	80	24	79	25	699	11
41-NJ	Aura; Typic Fragiudult; sandy loam; coarse-loamy, mixed, mesic	0.7	6.18	6.3	3.7	7.7	4.9	67	42	81	16	662	12
43-PA	Hublersburg; Typic Hapludult; silty clay loam; clayey, illitic, mesic	1.6	5.90	5.5	3.5	8.0	5.6	83	36	83	26	1172	7
26-VT	Hadley; Typic Udifluvent; sandy loam; coarse-silty, mixed, mesic	1.5	6.47	8.4	8.4	10.6	7.7	105	50	84	20	761	11
38-ME	Nicholville; Aquic Haplorthod; sandy loam; coarse-silty, isotic, frigid	1.7	5.30	3.6	2.8	5.2	4.1	125	58	87	63	1623	5
28-CT	Woodbridge; Aquic Dystrudept; sandy loam; coarse-loamy, mixed, mesic	2.1	5.98	3.0	2.3	5.5	4.6	89	43	88	56	1639	5
37-MD	Mattapex; Aquic Hapludult; silt loam; fine-silty, mixed, mesic	1.0	6.38	9.2	5.9	11.3	7.6	90	45	98	25	928	11
5-DE	Kenansville; Arenic Hapludult; loam; loamy, siliceous, thermic	0.9	6.13	7.8	5.5	9.4	6.2	122	46	111	35	735	15
45-PA	Linden; Fluventic Dystrudept; sandy loam; coarse-loamy, mixed, mesic	0.6	5.78	9.3	7.2	12.2	8.5	71	58	123	20	607	20
18-NJ	Freehold; Typic Hapludult; sandy loam; fine-loamy, mixed, mesic	0.9	5.57	8.5	6.8	11.2	8.3	147	72	123	69	714	17
31-DE	Kenansville; Arenic Hapludult; loam; loamy, siliceous, thermic	1.1	5.88	11.3	8.4	13.1	9.6	123	60	138	23	548	25

Continued next page.

Table 2. Continued.

Experimental site-state	Soil series and taxonomy	Organic C	pH	M-COL	MM-COL	Soil test extractable P† M-ICP	MM-ICP	B-ICP	M1-ICP	M3-ICP	Soil test extractable Al MM-ICP	M3-ICP	M3 P/Al
30-DE	Sassafras; Typic Hapludult; loam; fine-loamy, siliceous, mesic	0.9	5.83	9.8	7.1	11.9	8.2	114	53	144	24	539	27
46-RI	Bridgehampton; Typic Dystrudept; silt loam; coarse-silty, mixed, mesic	1.6	5.58	7.6	6.3	11.8	9.8	268	94	160	131	1647	10
6-DE	Matapeake; Typic Hapludult; silt; fine-silty, mixed, mesic	0.9	6.44	17.6	14.9	19.2	14.1	208	84	176	25	837	21
49-VT	Nellis; Typic Eutrudept;; coarse-loamy, mixed, mesic	1.7	6.03	38.3	28.7	41.6	28.1	148	114	197	7	817	24
25-RI	Merrimac; Typic Dystrudept; sandy loam; sandy, mixed, mesic	1.2	5.32	12.4	9.1	16.1	10.7	294	76	225	68	913	25
8-MA	Merrimac; Typic Dystrudept; sandy loam; sandy, mixed, mesic	1.2	6.20	9.8	7.1	11.7	7.9	346	135	235	40	962	24
17-NH	Hollis-Charlton; Lithic-Typic Dystrudept; sandy loam; loamy-coarse loamy, mixed, mesic	3.1	5.52	9.6	9.4	14.0	10.4	374	116	238	83	1378	17
44-PA	Hagerstown; Typic Hapludalf; silt loam; fine, mixed, mesic	1.5	6.30	39.0	27.6	42.5	29.8	239	150	248	12	1054	24
47-RI	Hinckley; Typic Udorthent; sandy loam; sandy-skeletal, mixed, mesic	1.2	5.86	11.2	8.8	15.1	11.3	261	89	255	81	1412	18
7-MA	Hadley; Typic Udifluvent; sandy loam; coarse-silty, mixed, mesic	1.4	6.90	19.0	16.2	20.7	15.9	427	202	259	27	1092	24
40-NH	Hollis-Charlton; Lithic/Typic Dystrudept; sandy loam; loamy/coarse loamy, mixed, mesic	2.2	5.33	10.5	7.3	13.4	9.3	279	95	295	66	1665	18
12-ME	Caribou; Typic Haplorthod; loam; fine-loamy, isotic, frigid	1.2	6.63	20.0	17.3	22.4	18.6	420	247	307	49	1292	24
35-MA	Merrimac; Typic Dystrudept; sandy loam; sandy, mixed, mesic	1.2	5.58	12.2	8.4	15.1	10.3	285	132	319	48	1147	28
21-PA	Braceville; Typic Fragiudept; loam; coarse-loamy, mixed, mesic	2.5	6.30	24.3	19.8	29.1	21.0	505	226	326	39	1149	28
11-ME	Bangor; Typic Haplorthod; silt loam; coarse-loamy, isotic, frigid	2.3	5.41	16.1	14.7	21.3	16.7	508	209	338	70	1342	25
34-MA	Hadley; Typic Udifluvent; sandy loam; coarse-silty, mixed, mesic	1.8	5.58	22.3	15.5	24.7	17.6	514	238	418	28	1525	27

† Soil P determined by five extractants: M-COL, Morgan-Colorometric; MM-COL, Modified Morgan-Colorometric;M-ICP, Morgan-ICP; MM-ICP, Modified Morgan-ICP; B-ICP, Bray-1-ICP; M1-ICP, Mehlich-1-ICP; and M3-ICP, Mehlich-3-ICP; soil Al determined by Modified Morgan and Mehlich-3.

organic C, and extractable P and Al by the Mehlich-1, Mehlich-3, and Bray-P1 methods. The same set of samples was also analyzed for extractable P and Al at the University of Maine Soil Test Lab by the Morgan method and the Modified Morgan soil test method. All soil test methods were performed following *Recommended Soil Test Procedures for the Northeast* (Sims and Wolf, 1995). All extractions were analyzed by ICP, but P extracted using Morgan and Modified Morgon solution was also determined colorimetrically.

Plant height was determined 35 d after planting on 30 random plants per plot by measuring from the soil surface to the tip of the uppermost fully expanded leaf. At approximately the midsilk stage, the percentage of plants with silk emergence, based on 50 random plants, was recorded. Ear leaf (refers to the leaf attached to the node that is opposite and below the primary ear) samples were collected from 10 randomly selected plants from each plot at about the midsilk stage. Tissue samples were dried at 70°C for 48 h, ground to pass a 1-mm screen, digested with nitric acid and hydrochloric acid, and analyzed colorimetrically for P at the University of New Hampshire Soil Test Lab. Grain yield or silage yield was determined by harvesting of a minimum of 6.1 m of row length from each of the two center rows of each plot. Grain yields were adjusted to a uniform moisture content of 155 g kg^{-1} and silage yields were adjusted to a dry weight basis. Relative yields were defined as the mean yield of the control (no P fertilizer added) plots expressed as percentages of the mean yield of P broadcast plots for each site.

All data were analyzed using the Statistical Analysis System (SAS Inst., Cary, NC). Fisher's Least Significant Difference (LSD) test was used for mean separation within each individual site. An analysis of variance was performed on the combined data using the PROC MIXED procedure. Sites, years, and blocks were considered random variables in the model because we were interested in making inferences for our fixed effects (treatments) for any year and site and not only for the sites and years represented by our data. Differences between means were tested using the Tukey-Kramer test of significance for the combined analysis.

Statistical significance was assessed at the 0.05 level except for corn grain and silage yield, which was assessed at 0.10. The Cate-Nelson method (Cate and Nelson, 1971) was calculated using the GLM procedure in the SAS statistical software (Goodnight et al., 1990) while selecting a horizontal critical level of 93% relative yield.

RESULTS AND DISCUSSION

Across the 34 sites where the corn was harvested for grain, the yields ranged from 2.5 to 17.7 Mg ha^{-1}, and across the 17 sites harvested as silage, the yields ranged from 7.94 to 23.50 Mg ha^{-1} (Table 3). Variation in rainfall and irrigation practice among sites were factors influencing crop yield. From a total of 51 experimental sites harvested as grain or silage, only nine sites exhibited yield increases ($P < 0.10$) from the 60 kg ha^{-1} P broadcast fertilization and only four sites from the 15 kg ha^{-1} P band treatment.

The combined analysis of variance (Table 4) for sites harvested as grain reveals that the broadcast treatment increased yield, whereas the band treatment did not. Combined analysis of variance over sites harvested for silage was not significant for either treatment.

Table 3. Corn grain and silage yield response to band and broadcast applied P at 51 experimental sites in 1998 and 1999.

	Grain			Statistics ($P > F$)			
Exp. site-state	Control	Band	Broadcast	Treatment	Control vs. BN	Control vs. BC	BN vs. BC†
	Mg ha^{-1}						
19-NJ	11.5	11.1	11.4	0.79	0.53	0.85	0.65
50-WV	7.0	7.3	8.4	0.02	0.38	0.01	0.02
23-PA	9.3	9.9	9.8	0.52	0.32	0.36	0.92
51-WV	4.0	4.1	4.7	0.16	0.80	0.08	0.12
10-MD	6.8	6.5	6.9	0.74	0.57	0.89	0.48
9-MD	5.6	6.6	6.6	0.34	0.21	0.21	1.00
36-MD	1.5	1.5	1.4	0.41	0.57	0.44	0.20
3-DE	8.6	9.4	9.1	0.31	0.14	0.35	0.53
22-PA	7.3	7.9	7.9	0.25	0.16	0.16	1.00
20-NJ	14.3	14.5	14.6	0.50	0.54	0.26	0.56
24-PA	9.4	11.1	11.5	0.08	0.07	0.04	0.70
32-DE	6.8	6.8	7.2	0.16	0.75	0.08	0.13
33-DE	4.3	5.1	5.3	0.37	0.26	0.21	0.87
42-NJ	17.4	17.7	17.7	0.34	0.21	0.20	0.97
4-DE	8.2	7.1	7.2	0.21	0.11	0.16	0.79
41-NJ	15.0	15.1	15.5	0.05	0.94	0.03	0.03
43-PA	6.4	6.2	7.7	0.04	0.64	0.04	0.02
37-MD	2.1	2.1	1.9	0.32	0.94	0.21	0.19
5-DE	5.6	5.6	5.3	0.95	0.98	0.78	0.79
45-PA	12.3	12.9	13.1	0.36	0.28	0.19	0.77
18-NJ	14.9	15.6	15.0	0.15	0.07	0.69	0.13
31-DE	11.3	9.4	10.7	0.26	0.13	0.64	0.25
30-DE	9.5	10.0	9.4	0.83	0.62	0.97	0.59
46-RI	7.2	6.4	8.4	0.06	0.28	0.14	0.02
6-DE	5.6	5.5	6.6	0.20	0.95	0.13	0.12
25-RI	5.0	4.7	5.7	0.73	0.72	0.39	0.26
8-MA	11.5	11.7	9.8	0.25	0.82	0.19	0.14
44-PA	2.5	3.7	3.1	0.53	0.29	0.56	0.59
47-RI	5.3	6.9	6.3	0.28	0.13	0.31	0.56
7-MA	14.6	14.9	16.4	0.06	0.63	0.03	0.05
35-MA	9.0	11.0	11.8	0.14	0.16	0.06	0.53
21-PA	7.4	7.7	7.7	0.91	0.73	0.71	0.98
11-ME	5.3	5.0	5.3	0.51	0.44	0.73	0.28
34-MA	16.8	16.1	15.0	0.18	0.43	0.07	0.24
	Silage						
	Mg ha^{-1}						
27-VT	7.92	9.43	11.28	0.04	0.17	0.01	0.10
48-VT	10.81	11.03	11.52	0.36	0.66	0.18	0.34
1-CT	17.73	16.51	17.93	0.33	0.24	0.84	0.18
16-NH	14.62	16.02	17.81	0.46	0.58	0.24	0.49
29-CT	64.08	66.05	64.63	0.88	0.77	0.84	0.63
14-ME	55.55	54.88	60.87	0.55	0.47	0.30	0.74
2-CT	18.63	18.75	18.97	0.94	0.91	0.75	0.83
13-ME	53.26	52.70	58.74	0.67	0.93	0.43	0.48
15-NH	18.07	16.95	15.53	0.67	0.51	0.85	0.41
39-NH	20.13	21.82	20.74	0.36	0.17	0.60	0.36
26-VT	18.25	16.16	18.64	0.001	0.002	0.33	0.001
38-ME	13.56	12.84	13.46	0.61	0.39	0.96	0.42
28-CT	37.20	53.13	45.43	0.18	0.08	0.31	0.34
49-VT	11.04	12.62	11.38	0.31	0.16	0.74	0.25
17-NH	22.74	20.10	23.46	0.17	0.16	0.67	0.08
40-NH	17.29	16.98	16.80	0.98	0.91	0.86	0.95
12-ME	41.78	47.38	45.47	0.15	0.07	0.51	0.17

† BN, band 15 kg ha^{-1} of P; BC, broadcast 60 kg ha^{-1} of P.

Early season growth indicators such as height and silking were more responsive to P fertilization than crop yield was for either treatment. Twelve of the 47 experimental sites where plant height data were collected exhibited growth increases to P fertilization and one site exhibited a decrease. The combined analysis of variance (Table 4) revealed that early season plant height increases were highly significant for both P fertilizer treatments. Eight of the 42 experimental sites where silking data was collected exhibited advancements in the rate of silk emergence and the combined analysis of variance indicated that the overall effect of P fertilization was highly significant for both treatments (Table 4).

Early season corn plant growth increases to the P treatments were often visually apparent in the field, and these early growth differences were sometimes associated with crop yield increases. Thus, early season growth increases of corn to P fertilization may sometimes translate into increased crop yield, but this relationship is not strong, with an r value of 0.45. Previous research (Mallarino et al., 1999) has shown that early corn growth enhancements from banded P often do not translate into increased crop yield at maturity.

Tissue analysis of the earleaf revealed that, of the 37 sites that were sampled, the P concentration ranged from 1.93 to 3.45 g kg^{-1}. Only one site had an earleaf

Table 4. Corn plant height at 35 d after planting, silking percentage, earleaf P concentration, and grain and silage yield responses combined over experimental sites and years.

Year	1998	1999	1998–1999
		Plant height, cm	
Control	60	49	55
Band	64	52	59
Broadcast	64	54	59
		$P > F$	
Treatment	0.0001	0.0001	0.0001
Control vs. BN	0.0001	0.003	0.0001
Control vs. BC	0.0004	0.0001	0.0001
BN vs. BC†	0.65	0.24	0.88
n	26	22	48
		Silking, %	
Control	53	57	55
Band	61	62	62
Broadcast	62	67	65
		$P > F$	
Treatment	0.0002	0.0001	0.0001
Control vs. BN	0.003	0.04	0.0002
Control vs. BC	0.0003	0.0001	0.0001
BN vs. BC	0.85	0.06	0.10
n	20	22	42
		Earleaf P, g kg^{-1}	
Control	28	25	26
Band	28	25	26
Broadcast	28	24	27
		$P > F$	
Treatment	0.09	0.58	0.60
Control vs. BN	0.95	0.97	1.00
Control vs. BC	0.20	0.74	0.68
BN vs. BC	0.11	0.58	0.64
n	23	14	37
		Grain, Mg ha^{-1}	
Control	8.8	9.1	8.9
Band	9.0	9.4	9.2
Broadcast	9.3	9.6	9.5
		$P > F$	
Treatment	0.10	0.05	0.005
Control vs. BN	0.44	0.42	0.18
Control vs. BC	0.09	0.04	0.003
BN vs. BC	0.62	0.43	0.27
n	17	17	34
		Silage, Mg ha^{-1}	
Control	15.68	14.75	15.29
Band	15.38	15.75	15.53
Broadcast	16.39	15.28	15.93
		$P > F$	
Treatment	0.06	0.20	0.18
Control vs. BN	0.77	0.17	0.76
Control vs. BC	0.24	0.60	0.16
BN vs. BC	0.06	0.68	0.49
n	10	7	17
		Grain moisture, g kg^{-1}	
Control	238	249	244
Band	238	248	243
Broadcast	239	242	241
		$P > F$	
Treatment	0.93	0.03	0.02
Control vs. BN	0.99	0.96	0.99
Control vs. BC	0.93	0.04	0.19
BN vs. BC	0.97	0.07	0.24
n	16	15	31

† BN, band 15 kg ha^{-1} of P; BC, broadcast 60 kg ha^{-1} of P.

P concentration below the normal expected range of 2 to 4 g kg^{-1} (Jones et al., 1990). Just two sites for the broadcast treatment and one site for the band treatment exhibited increases in tissue P concentration. The combined analysis of variance over sites for earleaf P concentration on the P treatments was not significant (Table 4).

Grain moisture content measured at harvest averaged 243 g kg^{-1} for the controls, 243 for the band treatment, and 240 g kg^{-1} for the broadcast treatment. Only two experimental sites for the broadcast treatment and one site for the band treatment exhibited reductions in grain moisture content due to the treatments but the combined analysis of variance over sites for grain moisture content was significant (Table 4).

When averaged across sites, corn yield, early growth, and other crop response indicators were generally more responsive to 60 kg ha^{-1} broadcast than the 15 kg ha^{-1} band treatment. For this reason, the relationships between crop response and soil test P were examined from the perspective of the high rate of broadcast P (Fig. 1 and 2). Others studies (Mengel et al., 1988; Randall and Hoeft, 1988; Rehm et al., 1988) have similarly shown that benefits of banded P diminish in comparison to high rates of broadcast P.

Previous soil test calibration research in Pennsylvania (Beegle and Oravec, 1990) and in Iowa (Mallarino and Blackmer, 1992) used Cate-Nelson analysis (Cate and Nelson, 1965) to select the soil test P critical concentration for corn. In the Iowa study, several methods of determining critical concentrations were compared and the Cate-Nelson model was reported as the best. In the present study, employing Cate-Nelson analysis on the data from the 51 experimental sites failed to clearly identify soil test P critical levels for any of the five soil test methods.

Preplant soil test P levels ranged from very low to very high across the 51 experimental sites (Table 2). The number of sites that had soil test P levels below current critical levels varied depending on the soil test extractant and a state's particular soil test critical level in use (Table 1). For example, the percentage of experimental sites that had initial soil test P levels below the current critical level ranged from 14 to 65% of the sites. By definition, experimental sites that test below the soil test critical level are likely to respond positively to the application of P fertilizer (Mallarino and Blackmer, 1992). Results show that 17 to 43% of those sites testing below the critical level exhibited a yield increase to the application of P fertilizer (Table 1) and 25 to 50% of the sites testing below the critical level exhibited an early growth increase to P fertilizer. Also, some sites that tested below the particular soil test critical levels in use did not respond to P fertilizer, and a few sites (depending on the state designated critical level) that would be predicted to not respond did exhibit responses to P fertilizer (Fig. 1 and 2). Depending on the soil test critical level employed, two to six of the nine yield responsive sites had soil test P levels above the critical level. All of these sites, however, occurred in the soil test range (Table 1) where maintenance (crop removal or partial crop removal) rates of P fertilization (Heckman et al., 2003), ranging from 20 to 80 kg ha $^{-1}$ P depending on the grain or silage yield goal, would be recommended. Thus, current soil test recommendations for maintenance applications of P would have likely protected against a potential loss of corn yield at most of the responsive experimental sites that had soil test P levels above the critical level. Some

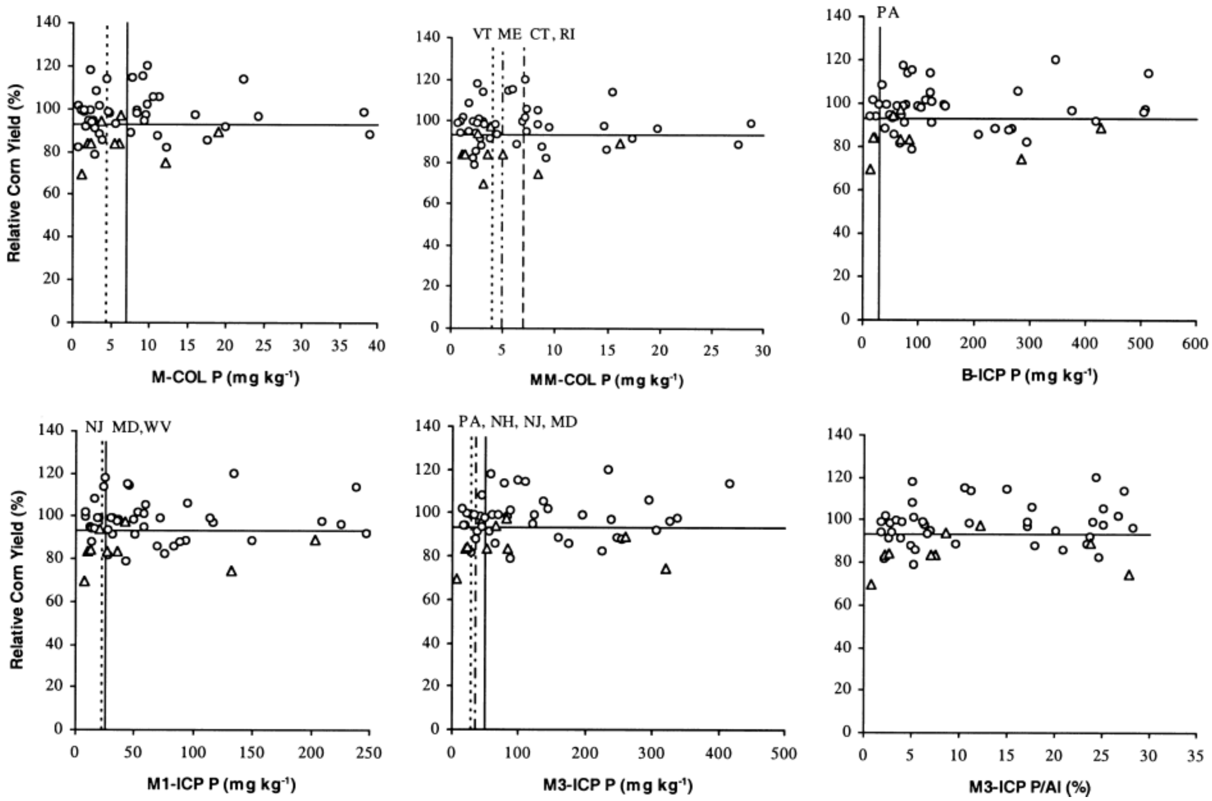

Fig. 1. Relationships between soil P extracted by five soil test extractants and relative yield as calculated based on the broadcast treatment. Triangle symbols are statistically significant at the $P > F$ 0.10 level; circle symbols are not significant. Vertical lines indicate current soil test P critical levels for individual states.

experimental sites (7-MA and 35-MA in Tables 2 and 3) were problematic in that they exhibited yield increases at very high soil test P levels. Site 35-MA, for example, had a soil test P level of 319 mg kg^{-1} M3-ICP with a large and significant yield increase (relative yield = 75%).

The M3-ICP P/Al ratio was shown by Khiari et al. (2000) to be a reliable method for making both agronomic and environmental P recommendations for potato production in Quebec, and this approach has been adopted by the province for other field crops as well (CRAAQ, 2003). Consequently, we included yield and plant height response data for the P/Al ratio for comparison with that for M3-ICP P (Fig. 1 and 2) but this approach also did not exhibit a clear relationship.

Soil testing for Morgan and Modified-Morgan P are based on colorometric, not ICP, analysis of the extracts. States that use these extractants perform colorometric analysis (except Maine, which performs ICP analysis but adjusts results to colorometric based on correlation) and their threshold levels are based on colorometric P analysis. While results from ICP and colorometric analysis are well correlated (R^2 of 0.99 and 0.98), those from colorometric are 2.0 and 1.5 mg kg^{-1} lower for Morgan and Modified-Morgan, respectively (Fig. 3). These represent substantial differences given critical levels in the range of 4 to 7 mg kg^{-1}.

The calibration data obtained from the present study and the relationships examined between soil test P and relative yield do not necessarily validate the currently used soil test P critical levels nor does the data enable much refinement. This study shows that the current critical levels frequently permit both types of errors in soil test prediction; indicating a need for P fertilization when it may not be needed (data in upper left quadrant) and not indicating a need for P fertilization when it may be needed (data in lower right quadrant) (Fig. 1). Fortunately, in the case of P recommendations, the second type of error, that could be a crop yield limiting factor, will usually be avoided by the use of crop removal or maintenance application rates of P. Nevertheless, given the environmental and economic concerns related to P fertility, soil testing laboratories are burdened with the responsibility of providing accurate recommendations. With the considerable need for improvement in the accuracy of P fertility recommendations, improving soil test predictions for P will continue to be a research priority.

The difficulties with soil test P calibration research are highlighted by the contrasting recent success in establishing clearly defined presidedress soil nitrate test (Magdoff, 1991) critical levels. Most of the states in the region have independently conducted research and have come to remarkably close agreement that the PSNT critical level for corn is between 20 and 25 mg kg^{-1} (Heckman, 2002). Even on other annual crops, the PSNT critical level is in the same range, and the PSNT is consistently about 85% accurate for correctly predicting whether N is needed. The situations for N and P are different for many reasons, but first, crops grown on soils of

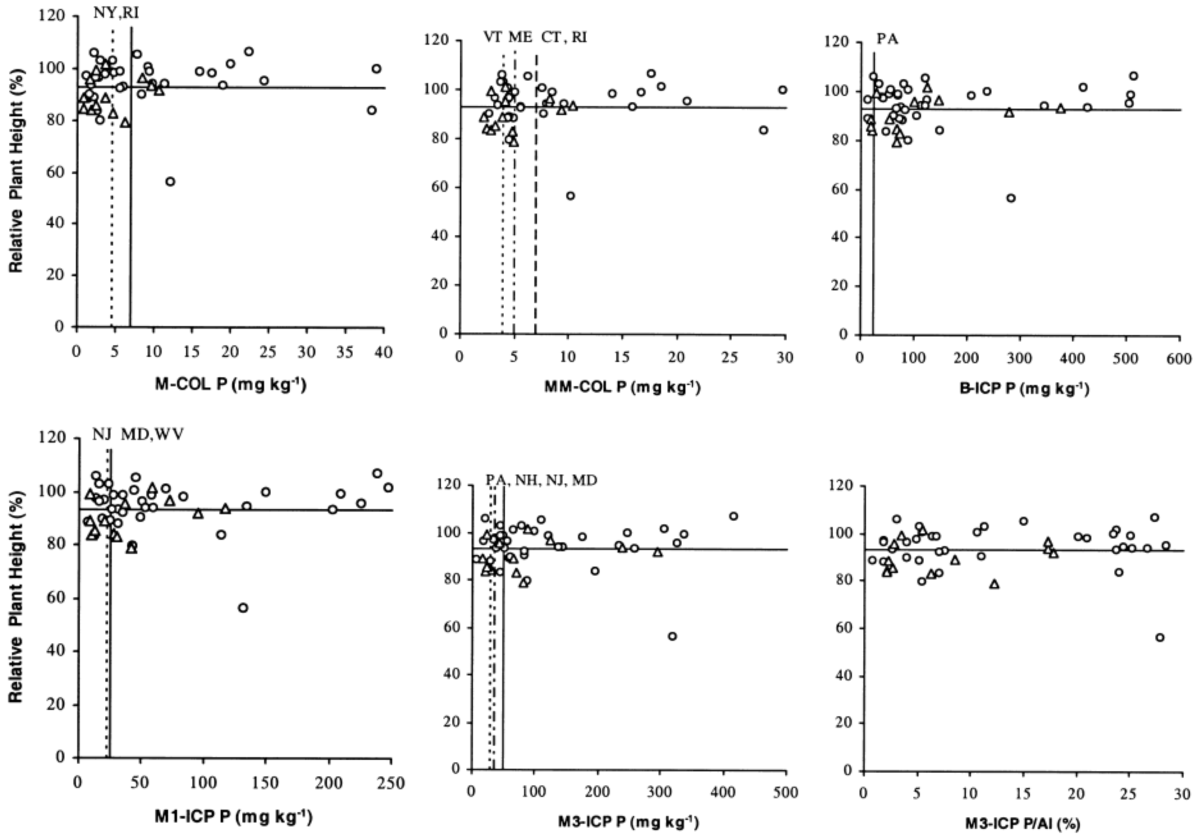

Fig. 2. Relationships between soil P extracted by five soil test extractants and relative plant height at 35 d after planting as calculated based on the broadcast treatment. Triangle symbols are statistically significant at the $P > F$ 0.05 level; circle symbols are not significant. Vertical lines indicate current soil test P critical levels for individual states.

this region are typically much more responsive to N than to P. With the abundance of high P fertility soils in the region (Fixen, 2002), it is becoming increasingly difficult to find good field sites for soil test P calibration research (Beegle and Oravec, 1990). Second, the chemistry and transport mechanisms for nitrate uptake and for P uptake in the soil–plant system are fundamentally different, with nitrate being very soluble and moving to the root primarily by mass flow, and P being strongly adsorbed and moving to the root primarily by diffusion. While proposals (Barber, 1995) to improve soil testing for P using a mechanistic approach may hold promise, it

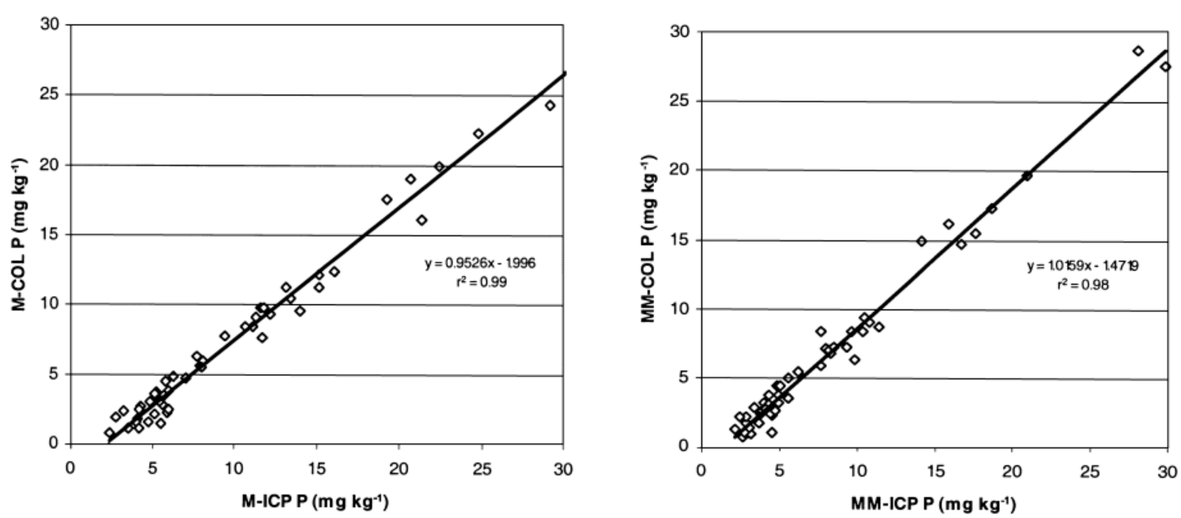

Fig. 3. Morgan and Modified Morgan P analyzed by ICP and colorometric methods.

has not yet been realized, and the development of reliable predictors for crop responses to P fertilizer continues to be a research challenge brought on with increasing urgency as soil test P levels are now being used for regulatory purposes.

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